SEAN GALLUP/GETTY

Figure 1 | Rivers of meltwater carve into the Greenland ice sheet.

Climate science

The worst is yet to come for the Greenland ice sheet

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An assessment of past, present and future ice loss from the Greenland ice sheet shows that rates of loss in the twenty-first century will be much higher than those at any time during the past 11,700 years. **See p.70**

The Greenland ice sheet is losing ice at an increasing rate, owing to rising air and ocean temperatures[1,2]. Melting of the ice sheet is currently increasing global mean sea level by about 0.7 millimetres per year (see go.nature.com/3mrkuw8), but models predict[3] that rates could reach between 2 and 7 mm per year by 2100. However, observed and predicted rates of ice-sheet loss have never been evaluated in the context of natural ice-sheet variability. On page 70, Briner *et al.*[4] fill this knowledge gap, by simulating the evolution of the Greenland ice sheet throughout the Holocene epoch – that is, over the past 11,700 years. They show that, although present melt rates are comparable to the highest rates during the Holocene, future rates will probably exceed them.

The current recession of Greenland's ice margin is led by the retreat of outlet glaciers – large rivers of ice ending in narrow fjords that drain the ice sheet's interior. This retreat is occurring in response to increased ocean temperatures, and will continue to play a key part in the loss of ice mass in the twenty-first century[3]. However, the flow of outlet glaciers is dictated by the geometry of the underlying submarine channels, which extend only about 100 kilometres inland for large glaciers. Consequently, the area of the ice sheet that is in contact with the ocean is much smaller than the area exposed to the atmosphere (Fig. 1). Over timescales of millennia, therefore, atmospheric conditions such as changes in precipitation and air temperature are more

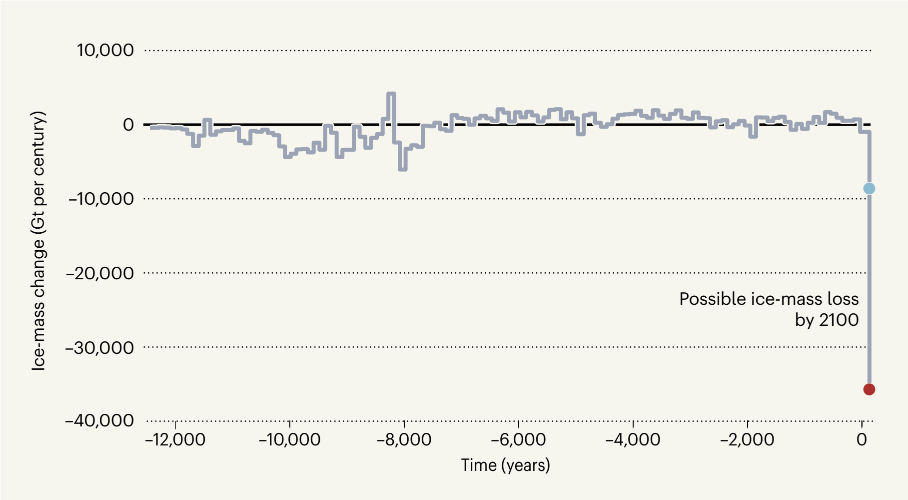

Figure 2 | Past, present and future ice loss for the Greenland ice sheet. Briner *et al.*[4] have modelled ice-mass change from the west-southwest portion of the Greenland ice sheet, from 11,700 years ago up to the year 2100. They find that ice mass was lost at a fairly steady rate between 11,700 and 7,000 years ago, peaking at about 6,000 gigatonnes per century. Rates of ice loss then decreased, until recent years. Currently, ice mass is being lost at about 6,100 Gt per century. However, the authors predict that rates of loss will increase drastically in the future, to between 8,800 (blue dot) and 35,900 (red) Gt per century by 2100. The grey line shown here represents the mean of all the simulations performed by the authors.

relevant to ice extent than are the retreat of peripheral glaciers.

To calculate the amount of ice that was gained or lost per year during the Holocene, previous studies have typically relied on estimating past air temperatures from standardized ratios (denoted by δ^{18}O) of the abundances of the stable isotopes oxygen-18 and oxygen-16 in water molecules that make up the ice cores. Because water that contains the isotope ^{18}O evaporates less rapidly and condenses more easily than does water containing ^{16}O, δ^{18}O provides information about the air temperature at times when snow fell. A simple scaling between the reconstruction of past air temperature and present-day precipitation is then used to estimate past precipitation.

Briner and colleagues take a different approach. Rather than using δ^{18}O reconstructions alone, the authors make use of a set of climate histories published this year[5], which were produced by combining a climate model with δ^{18}O reconstructions of climate and measures of ice-sheet thickness from ice cores. The climate model calculates changes in precipitation in response to changes in the shape of the ice sheet, and provides a better reconstruction of precipitation than does the scaling approach alone.

The authors used these histories to model the evolution of the west-southwest (WSW) portion of the ice sheet at a high-enough spatial resolution to reveal key physical processes. They chose this relatively small area for two reasons. First, reducing the area studied lowers computational costs, which are high when modelling at high resolution. Second, this particular portion of the ice sheet lies mostly over the land and so is easier to model: sea borders add another layer of complexity. This area is thought to be representative of the whole ice sheet[6], but future work should confirm this.

Using this model, Briner *et al.* produced an ice-margin time series that runs from 11,700 years ago until the year 2100. Looking to the past, the authors found that the WSW ice sheet retreated eastwards between 12,000 and 7,000 years ago, after which time changes were minimal. At peak ice loss, the ice sheet was reducing by up to 6,000 gigatonnes per century. The time series indicates that mass

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loss today is at a similar level, about 6,100 Gt per century. But the worst is yet to come: ice-sheet loss in the twenty-first century is predicted to be between 8,800 and 35,900 Gt, depending on how much the concentration of greenhouse gases in the atmosphere increases over the years (Fig. 2). This would lead to a sea-level rise of between 2 and 10 cm by 2100.

Accurate predictions of future mass loss from Greenland and Antarctica are of great societal importance — so a key question is whether the authors' model is accurate. A good way to assess the fidelity of a model is through history matching, in which a model is tested by inputting data about known or closely estimated past events to see how well the output matches observations. Briner and colleagues take this approach. The authors show that their estimates for the Holocene are in good agreement with recently published geological reconstructions of Holocene ice-margin positions in WSW Greenland[7].

Reproducing contemporary mass loss accurately remains a challenge, but it is crucial to making confident predictions of Greenland's future contribution to rising sea levels. A model that underestimates today's mass loss is also likely to underestimate tomorrow's. Although Briner *et al.* show that their model is able to track Holocene ice-margin positions, future work needs to demonstrate that the model can also accurately reproduce contemporary mass loss. In fact, any models used to estimate future mass loss should be evaluated on the basis of how well they match historical and contemporary observations.

Thanks to the work of Briner and colleagues, we are now one step closer to the goal of accurately and confidently predicting mass loss from the Greenland ice sheet. However, we are also increasingly certain that we are about to experience unprecedented rates of ice loss from Greenland, unless greenhouse-gas emissions are substantially reduced.

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